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ON ULTRASONIC STANDING WAVES

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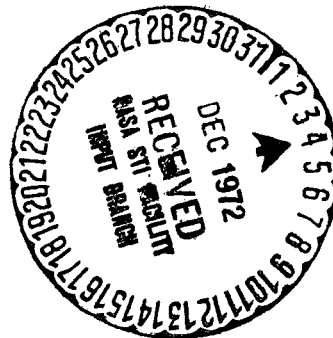
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CONDITIONS OF COHERENCE IN DIFFRACTION SPECTRA PRODUCED IN LIQUIDS  
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ABSTRACT. Experiments, conducted to determine which of the different diffraction spectra produced on ultrasonic standing waves in liquids through the diffraction of light are coherent, i.e., can be brought to interfere with each other, are described. The result is the following: any arbitrary pairing of two spectra with even ordinal numbers (including zero order) possesses at least one common component of coherent light; the same is true for any pairing from the group of spectra with odd ordinal numbers. On the other hand, any spectrum of the first group is completely incoherent in combination with any spectrum of the second group. The patterns of ultrasonic standing waves produced by the superposition of several or all of the diffraction spectra, may also be explained by such coherence properties. Experimentally determined coherence properties are exactly those obtained from the assumption that higher diffraction spectra originate in multiple diffraction (Brillouin theory).

1. Introduction

Diffraction spectra produced in the diffraction of light by standing ultrasonic waves in liquids can be recombined with a lens and brought to interference; it is also possible to produce an actual optical reproduction of these sound waves. Experiments of this type were first performed by Bachem, Hiedemann and Asbach [1], and Hiedemann et al. [2] subsequently based a new precision method for the determination of ultrasonic velocities in liquids on this effect. Even the first images of ultrasonic waves published were excellent; this is remarkable, because the authors at that time had no certainty concerning the generation of the patterns; they considered them to be schlieren images. The fact that the experimental apparatus used actually yields an optical reproduction of the sound waves, was established shortly afterwards by the work of Debye, Sack and Coulon [3], who worked on the problem simultaneously but independently. The

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\* Numbers in the margin indicate pagination in the foreign text.

authors point out that theory requires that the light undergo a Doppler effect during diffraction by propagating ultrasonic waves. This shifts the frequency of the incident light  $\nu_0$  in  $\nu_{+n} = \nu_0 + n\Omega$  and  $\nu_{-n} = \nu_0 - n\Omega$ , where  $\nu_{+n}$ , or  $\nu_{-n}$ , are the frequencies of the light diffracted in the  $+n^{\text{th}}$  or  $-n^{\text{th}}$  order and  $\Omega$  is the frequency of sound. It must be concluded that in the diffraction of light by ultrasonic standing waves, which are generated by the superposition of two waves propagating in opposite directions, in each of the two  $n^{\text{th}}$  orders both of the  $\nu_0 + n\Omega$  and  $\nu_0 - n\Omega$  frequencies are present simultaneously so that the two orders contain coherent light and produce interference upon superposition. It is therefore possible, by shielding to corresponding  $n^{\text{th}}$  orders and bringing them to interference, to reproduce ultrasonic waves. If all shielding is eliminated and all of the orders are superposed, interference phenomena are still produced in accordance with the above consideration, i.e. by the addition of the intensities of  $n$  number of reproductions produced by  $n$  pairs of diffraction spectra. This interference pattern then is in agreement with the image of ultrasonic waves obtained by Bachem, Hiedemann and Asbach. Debye, Sack and Coulon, however, were not interested in standing waves, but show that coherence relationships exist between individual spectra in light diffraction on propagating waves and that even arbitrary spectra with different ordinal numbers are capable of interference. Although such spectra have different frequencies, the floating light that appears and is due to the coherence can still be made visible by intermittent illumination with a Kerr cell. This thus makes it possible to reproduce even propagating ultrasonic waves, which has been accomplished recently by Bachem [4], again without this theoretical explanation.

Conditions existing during the reproduction of standing sound waves still appear to justify a more detailed investigation. In addition to the theoretical interest, e.g. the question of how to obtain reproductions of optimum quality of such waves is experimentally important, because among the methods of determining the velocity of sound in liquids, the method based on the reproduction and measurement of such waves within their frequency range has attained clear superiority with respect to accuracy.

## 2. Experimental Apparatus

The experimental arrangement was a conventional one, so that a detailed description is not necessary; let us merely emphasize the following items. It is recommended to use achromatic lenses for reproduction, because then the interferences occur at the same positions for all wavelengths of light, so that they remain visible even if white light is used in the diffraction. In the author's experiments, an incandescent filament or carbon arc lamp was used, projected by a condenser lens on a slit. If (see below) a certain amount of monochromatizing still became necessary, a Zeiss C monochromate filter was inserted between the condenser lens and the slit. The light of the slit was made parallel, as the secondary light source, by a Leitz projection objective lens ( $f = 40$  cm). Behind the objective was the trough (Leybold plate glass chest) with the liquid in which the ultrasonic waves were generated. Behind the trough, another Leitz projection objective was located ( $f = 50$  cm), in the focal plane of which the diffraction spectra were produced. This plane therefore also contained the diaphragms or slits used to separate the spectra to be examined from the multitude of diffraction spectra in existence. Since especially in the higher orders the individual colors of different diffraction spectra are overlapping, the isolation of certain spectra through these slits is frequently possible only if the light is monochromatized to some extent by the filter mentioned above. The distance of the second projection objective from the location where the ultrasonic waves penetrate the liquid was only slightly greater than the focal length, i.e. 55 cm, so that an image of the waves, enlarged approximately ten times, was produced at a distance of about  $5 \frac{1}{2}$  cm behind the system of lenses.

The following should be noted in connection with the generation of the ultrasonic waves: the piezo quartz generating the waves, ground for a frequency of 7500 kHz, had the form of a rectangle of 1 x 2 cm and stood with its 1 cm edge vertically and the 2 cm edge horizontally, i.e. parallel to the direction of the light beam. It was powered by a small two-tube (Philips TC 04/10) push-pull emitter, controlled either by a regenerative circuit or by a second emitter, the frequency of which was maintained constant with the aid of a control quartz, also ground for 7500 kHz frequency, in a Pierce circuit. Xylene was used as the liquid for the diffraction of light

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by ultrasonic waves. In order to form standing waves, the propagating waves were reflected from a planar wall; in this case, standing waves were generated even if the reflecting wall was not exactly perpendicular to the direction of propagation of the waves. The wave surfaces of the standing waves were obviously always planes parallel to the reflecting plane, but with oblique incidence (angle of incidence =  $\Theta$ , wavelength of propagating waves =  $\Lambda$ ) their intensity was reduced and their wavelength =  $\Lambda/\cos\Theta$ . The opposite wall of the Leybold trough was simply used as the reflecting plane, which for this reason was located as accurately as possible parallel to the surface of the piezo quartz emitting the sound waves. Since in this case measurements of wavelengths were to be performed, manual adjustment was adequate and it was sufficient to estimate directions visually. Due to always appreciable absorption of sound waves and also to the convection flow caused by the uneven heating of the liquid during the passage of the wave, the intensity of the standing waves was highest near the reflecting wall; for this reason, photography was always directed at an area as close as possible to the wall.

### 3. Interference Experiments with Two Diffraction Spectra

It has been stated in # 1 that the two diffraction spectra of each  $n^{\text{th}}$  order yield interferences upon their superposition; these can be interpreted as an image of the ultrasonic wave lattice. If  $d_n$  is the lattice constant of the lattice reproduced, then  $nd_n$  must be constant (i.e., =  $n\Lambda/2$ , where  $n$  is the linear magnification common to all images). The experiments yielded exactly the result expected from the theory. In Figure 1 a-c patterns generated by the diffraction spectra of the first, second, and fourth order are again enlarged with respect to the original photographs by a factor of about 4. It is seen that the ratio of the lattice constants of these images is actually 4:2:1. Since in xylene,  $\Lambda = 0.18$  cm for a sound frequency of 7500 kHz, the actual size of the area segments reproduced in the figures is only approximately  $0.0064 \text{ cm}^2$ . Figure 2 then presents the image formed by the interference of the first two orders in another enlargement.

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The image produced by the interference of the two  $n^{\text{th}}$  orders naturally does not permit the drawing of conclusions concerning the actual shape of ultrasonic waves generating the diffraction spectra. Even the well-known theorem that the image of an object obtained by the screening out of certain

orders is absolutely identical with the absolutely similar image of an object which contains these spectra as a complete diffraction spectrum, cannot be applied here, because the object to be reproduced is extended in space.

Additional experiments were now performed, in which the double slit used to screen out the two  $n^{\text{th}}$  orders was mounted on a carriage adjustable with a micrometer screw, so that the two slits, at a constant distance from each other, could be moved perpendicularly to the direction of the slit in the plane of the diffraction spectra. Then, an arbitrary shift of the slits always results in the isolation of two diffraction spectra, one of which possesses the (positive or negative) ordinal number  $m$ , and the other the number  $m + 2n$ . These experiments yielded the result, not expected because of the considerations presented in #1, that interferences may be generated even in the superposition of spectra of this type. These naturally have the same lattice constants as the interferences in the corresponding preceding experiment, i.e., for  $m = -n$ , but in general they are not as well visible; this obviously could not be expected, because if settings are correct, two spectra located symmetrically with respect to the zero order always have the same intensity, while for arbitrary spectra this is not necessarily true. In addition, the effect becomes more pronounced with the declining value of  $n$ .

For a study of coherence relationships in the diffraction spectra, obviously an investigation of the conditions in which no interferences are produced, is just as important. In this respect the experiments yielded the following result: no interferences are generated if arbitrary adjacent spectra,  $n$  and  $n + 1$ , are superposed. This, however, represents merely the most readily observed special case of the general case, in which no interference is observed; the superposition of two spectra, the ordinal number of which differ by an odd number.

All of the experiments described so far were performed with diffraction spectra from the zero to the sixth order; it may be assumed that diffraction spectra of higher orders would exhibit the same behavior and the following must be concluded.

With respect to their coherence conditions all diffraction spectra belong to two groups: the group of spectra with even ordinal numbers (including

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zero) and the spectra with odd ordinal numbers. All of the pairs of one group are at least partially coherent with each other; each two spectra of different groups are completely incoherent.

#### 4. Interference Experiments with Superposition of More than Two Diffraction Spectra

Even if only one double slit is used, under certain conditions in white light diffraction phenomena occur which are the result of the cooperation of more than two diffraction spectra. Specifically, in the isolation of higher spectra under certain conditions, two colors are isolated by a single slit, because individual spectral colors of different orders overlap, the colors belong to different orders. Obviously, the diffraction patterns produced by these two diffraction patterns are incoherent and the two intensities are simply added. An example of an interference pattern generated in this manner is presented in Figure 3. Naturally, the phenomenon can be made to disappear only by the insertion of a light filter; although without interest in itself, it is being mentioned because in experiments of the type described in the preceding paragraph, it may appear as a source of error.

Concerning the cooperation of more than two diffraction spectra of the same color in generating interference phenomena, the problem is highly complex, but it seems that it may be explained on the basis of known effects occurring in the diffraction of light by ultrasonic waves. With respect to the coherence of diffraction spectra of even or odd orders among themselves, it is confirmed by the interference phenomena in the superposition of three subsequent even or odd spectra. Figure 4 presents an interference pattern obtained with the superposition of orders +3, +1, and -1, such as is produced, e.g. also with the superposition of orders +2, 0 and -2. It is seen clearly that the strips are becoming significantly narrower than in the superposition of only two spectra. In addition, another system of strips, seen only faintly in the figure, may appear in the center between two strong, bright strips. These originate here in the interference of orders +3 and -1 and is generated if (adjustment not entirely symmetrical) the two orders are stronger than +1. /597

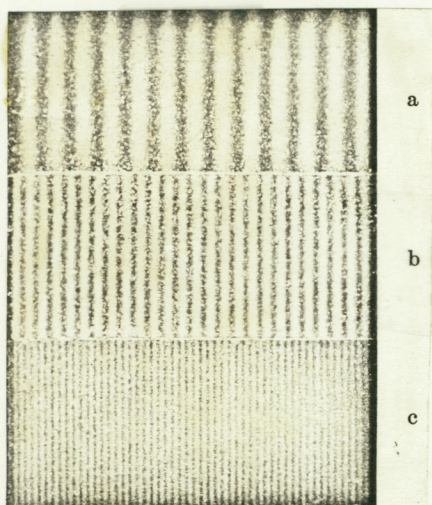


Figure 1. Interference in the superposition of (a) the first, (b) the second, and (c) the fourth orders.



Figure 5. Reproduction of a sound lattice with an intensity that is not constant in space (superposition of all diffraction patterns).



Figure 6. Reproduction of a sound lattice with "fine structure" caused by third orders.



Figure 2. Interferences in the superposition of the first orders (strongly enlarged in comparison with Figure 1a).

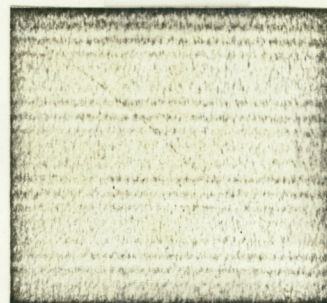


Figure 3. Combined interference pattern generated by the superposition of the intensities of two simple interferences (as in Fig. 1) with different ordinal numbers.

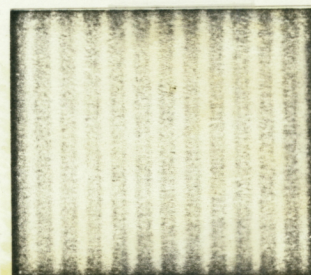


Figure 4. Interferences in the superposition of orders +3, +1, and -1.

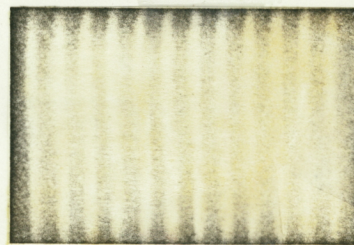


Figure 7. Sound lattice with disturbed development of plane waves.

Phenomena generated by the cooperation of several or all of the diffraction patterns are complicated by the fact that the individual spectra of the lower orders in general appear with highly different intensities. This effect, as shown by the author earlier [5], is visible only under special experimental conditions. Since in the usual experimental arrangement these conditions are not satisfied, all of the individual diffraction spectra of the lower orders appear with approximately the same intensities, but not because the light is being diffracted by all parts of the sound lattice with equal strength in the different orders, but only because the differences equalize each other on the average. In a reproduction of the ultrasonic sound lattice the differences again become visible and this is the cause of the locally differing appearance of the image. An example of this effect is presented in Figure 5; the figure represents an image obtained by the superposition of all of the diffraction spectra. The locations in the photograph where the center lines appear strong, originate in a diffraction phenomenon in which the first orders are weak and the second orders strong.

These differences in the intensity of the individual diffraction spectra are noticeable mainly, as shown by images presented elsewhere, in the first to third orders; as a result the differences in the appearance of the sound patterns, which consist in the absence of strong, bright strips of the first orders or in the occurrence of a "fine structure," i.e. a variable number of weak lines between the bright lines, also originate in the fact that the three pairs of diffraction spectra may be developed in a highly different manner. /598  
The coordination of individual strips necessary for such a statement with definite diffraction spectra can be performed simply and unambiguously by examining the behavior of the image to be interpreted if certain diffraction spectra are screened out. Figure 6 is a strongly enlarged reproduction of such a "fine structure" caused by third orders. It is evident that such structures in an image, if used for the measurement of wavelengths of sound, have a disturbing effect. However, they can be readily eliminated by varying the sound intensity or by filtering out the diffraction spectra involved. In such a case, one obtains the pattern of the sound lattice in the form of intensive, narrow, bright lines with the distance of the interferences of the first order as the lattice constants. Such a photograph has been published by Asbach, Bachem and Hiedemann [6], so that there is no need to reproduce it here.

As has been shown elsewhere, the intensity at which individual diffraction spectra occur also depends on the wavelength of light used. As a result, if white light is used, the pattern of the sound wave lattice will be colored, i.e., the image will be different for different wavelengths of light. Subjectively, this effect is readily seen. It is, however, difficult to record it photographically without the use of color filters, because the diffraction pattern generated is strongly dependent on intensity; two successive exposures thus reproduce the effect satisfactorily only if the intensity was identical in both cases.

Let us emphasize another condition which frequently obstructs satisfactory reproduction of sound wave lattices, i.e. the poor mounting of the piezo quartz; this results in the highly different emission of sound energy by individual parts of the quartz surface. (The emission from the quartz is easily examined by making a schlieren image of the sound field in the vicinity of the surface of the quartz, i.e. an exposure in which only a single isolated diffraction spectrum is effective, to avoid interferences). If such inhomogeneities are present in the emission of energy, the undisturbed generation is prevented and in place of the uniform, straight lines presented here, irregularly curved strips are formed, as shown in Figure 7. /599

Finally, let us mention a property of the images, which occurs occasionally without adequate explanation. It is found sometimes that the weaker systems of lines generated by the superposition of several spectra are not always situated completely symmetrically to the strong interferences of the first two orders. This lack of symmetry is probably due to some shortcoming in the mounting of the quartz, because it disappears in proportion to the care expended on the assembly of the experimental apparatus in this respect. The effect is not reproduced here.

## 5. Discussion of Experimental Results

Let us now discuss the problem of the theoretical explanation of the experimentally found fact that all of the diffraction spectra are divided into the two groups of even and odd orders, so that within each group all spectra are more or less coherent with each other, while two spectra from different groups are always incoherent. The answer to this question is likely to be closely related to the problem of the generation of higher orders in the

diffraction of light by sound waves. Brillouin's [7] theory claims that multiple diffraction is responsible and it is interesting that this effect also explains the coherence conditions observed here. Since in the case of standing sound waves, light diffracted in the first orders definitely has the frequencies of  $\nu_0 + \Omega$  and  $\nu_0 - \Omega$ , light diffracted in the second orders must contain the three frequencies  $\nu_0 + 2\Omega$ ,  $\nu_0$  and  $\nu_0 - 2\Omega$ . Generally, the following frequencies are then contained in the light of the two  $n^{\text{th}}$  orders

$$\nu_0 + n\Omega, \nu_0 + (n-2)\Omega, \dots, \nu_0 - (n-2)\Omega, \nu_0 - n\Omega$$

However, because in multiple diffraction light migrates not only in the higher orders but is obviously also rediffracted into the lower orders, two groups are formed: all of the spectra of even orders (including zero) contain light only of frequencies  $\nu_0 \pm k\Omega$ , where  $k$  assumes the value of all even numbers in the interval between 0 (inclusive) and  $n$  and all spectra of odd numbers contain only light of frequencies  $\nu_0 \pm l\Omega$ , where  $l$  travels through the series of odd numbers in this interval. /600

Obviously, these qualitative experiments do not yield information concerning the mass ratio in which different frequencies are present in the individual diffraction spectra; Ali [8], however, recently performed certain experiments from which such conclusions may be drawn. Results will appear in the detailed report to be published shortly. A summary precedes this paper.

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